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IMPROVING THE INTENSITY OF THE STEELMAKING TECHNOLOGICAL PROCESS BASED ON FUZZY LOGIC

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Abstract. *This article analyzes the application of a fuzzy logic system for controlling complex and uncertain technological processes occurring in a 30-ton Electric Arc Furnace (EAF-30). Research findings show that 80% of the melting process (42 minutes) is carried out using an electric arc. In traditional control systems, rapid fluctuations in arc current exceeding or falling below 17 kA have been identified as a cause of process interruptions. Therefore, this study proposes the fuzzification of arc current, voltage, and arc length using Gaussian membership functions. Based on critical thresholds—arc current in the range of 17–38 kA and voltage from -6% to +8%—linguistic variables were developed. Using the Mamdani algorithm, optimal electrode control during the 17–20-minute melting phase ensures improved energy efficiency, reduced electrode consumption, and increased product output. The research results demonstrate that integrating Fuzzy control into traditional systems is an effective approach for intensifying the steelmaking technological process.*

Keywords: *steelmaking, Fuzzy logic, arc current, arc length, Gaussian function, Mamdani algorithm, automatic control, electrodes movement.*

ПОВЫШЕНИЕ ИНТЕНСИВНОСТИ ТЕХНОЛОГИЧЕСКОГО ПРОЦЕССА СТАЛЕПЛАВЛЕНИЯ НА ОСНОВЕ НЕЧЕТКОЙ ЛОГИКИ

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Аннотация. *В данной статье проанализировано применение системы нечеткой логики для управления сложными и неопределенными технологическими процессами, происходящими в 30-тонной электродуговой сталеплавильной печи (ДСП-30). Результаты исследований показали, что 80% процесса плавки (42 минуты) осуществляется с использованием электрической дуги. В традиционных системах управления выявлены перебои в процессе, вызванные резкими колебаниями дугового тока выше или ниже порогового значения 17 кА. В связи с этим в работе предложена фаззификация дугового тока, напряжения и длины дуги на основе гауссовских функций принадлежности. Разработаны лингвистические переменные на основе критических границ: ток дуги в диапазоне 17–38 кА и напряжение от -6% до +8%. С использованием алгоритма Мамдани обеспечено оптимальное управление движением электродов в течение 17–20 минутной фазы плавки, что позволило повысить энергетическую эффективность, снизить расход электродов и увеличить производительность. Результаты исследования подтверждают,*

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что интеграция нечеткой логики в традиционные системы управления является эффективным решением для интенсификации сталеплавильного технологического процесса.
Ключевые слова: *сталеплавление, нечеткая логика, ток дуги, длина дуги, гауссовская функция, алгоритм Мамдани, автоматическое управление, движение электродов.*

FUZZY MANTIG‘I ASOSIDA PO‘LAT ERITISH TEXNOLOGIK JARAYONI INTENSIVLIGINI OSHIRISH

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Annotatsiya. *Ushbu maqolada 30 tonnalik elektrda po‘lat eritish pechida (DSP-30) yuz beradigan murakkab va noaniq texnologik jarayonlarni boshqarishda fuzzy mantiq tizimining qo‘llanilishi tahlil qilinadi. Tadqiqotlar natijasida aniqlandiki, eritish jarayonining 80 foizi (42 daqiqa) elektr yoy yordamida amalga oshiriladi. An’anaviy boshqaruv tizimlarida elektr yoy toki 17 kA dan keskin oshib yoki kamayib ketishi natijasida ishlab chiqarish to‘xtab qolish holatlari aniqlangan. Shu sababli, maqolada Fuzzy tizimi orqali elektr yoy toki, kuchlanishning Gauss funksiyalari asosida fuzzifikatsiya qilingan. Elektr yoy tokining 17–38 kA, kuchlanishning -6% dan +8% gacha bo‘lgan kritik chegaralari asosida lingvistik toifalar ishlab chiqilgan. Mamdani algoritmi asosida 17–20 daqiqalik eritish davrida elektrodlarning optimal boshqaruvi ta'minlanib, energiya tejamkorligi, elektrod sarfi kamayishi va mahsulot unumdorligi oshishi kabi natijalarga erishilgan. Tadqiqot natijalari Fuzzy boshqaruv tizimining an’anaviy tizimlarga integratsiya qilinishi orqali po‘lat eritish texnologik jarayonining samarali boshqaruvni ta’minlashi asosida texnologik jarayon intensivligini oshirishiq aniqlangan.*
Kalit so‘zlar: *po‘lat eritish, Fuzzy mantig‘i, elektr yoy toki, yoy uzunligi, Gauss funksiyasi, Mamdani algoritmi, avtomatik boshqaruv, elektrodlar harakati.*

Introduction. The metallurgical industry is one of the most important strategic sectors of a country's economy. This sector is developing not only by increasing production volumes but also through the expansion of export potential and modernization of technologies. In recent years, both the number of enterprises operating in the metallurgical industry and the volume of manufactured products have grown significantly. Specifically, while there were 974 enterprises in 2020, their number reached 1289 in 2024 as a result of the establishment of small and medium-sized joint ventures. These enterprises are divided into ferrous and non-ferrous metallurgy sectors based on the production process, with ferrous metallurgy being more complex and energy-intensive compared to the processing of non-ferrous metals. Furthermore, due to ongoing developments in construction and the economy in Uzbekistan, the demand for steel products as a leading product in the ferrous metallurgy sector is continuously increasing. However, it should be noted that the steelmaking process is one of the most complex technological processes to control automatically. In steel production technology, melting the primary charge using electrodes is significantly more complex and energy-intensive than rolling semi-finished steel products. Therefore, conducting research in the field of control systems for steelmaking technological processes in electric arc furnaces (EAFs) is of critical importance.

Literature analysis and methods. It is well known that the steelmaking process is multi-stage and non-linear in nature. Due to this non-linearity, the electrical parameters of the arc change sharply in a short period of time [1, 2, 3, 4]. This, in turn, complicates the optimal control of electrode movement, which is primarily based on maintaining the electric arc length within an optimal range. In such a complex process, the automatic control system in electric arc furnaces must operate rapidly and reliably. In this context, the electric arc current becomes a critical variable that directly affects the arc length between the electrodes and the metal

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during the melting of the primary charge. In short, due to the complexity, non-linearity, and dynamic nature of the EAF technological process, the application of expert operational knowledge becomes essential. Therefore, integrating modern and intelligent digitalization technologies to effectively monitor electrode movement speed and arc length in such a complex and non-linear process will enable the reduction of electrode wear and electric energy consumption.

For the development of a modern control system for the steelmaking technological process, a 30-ton EAF-30 currently operating in the republic was selected as the research object. In this furnace, a semi-finished steel product is produced in 55 minutes, of which 42 minutes—or 80% of the process time—is spent on electric arc melting. A hydraulic power regulator is used as the drive mechanism to control electrode movement, which is integrated into a PLC (Programmable Logic Controller) cabinet. The S7-1500 controller is installed in the PLC cabinet, and electrode movement is regulated using the TIA-Portal programming environment based on the control of arc length. When the EAF-30 is activated, due to the presence of solid scrap metal, arc current fluctuates sharply and the phase current imbalance increases. As a result, the arc current often exceeds the setpoint, and traditional control systems face significant challenges in maintaining precise current values during these rapid fluctuations. Consequently, abrupt increases or decreases in arc current can lead to interruptions in the steelmaking process, negatively impacting productivity.

Based on the practical and scientific studies conducted, it was determined that the use of fuzzy logic based on artificial intelligence is an effective approach to address the problems faced by current digitized control systems in steelmaking. Fuzzy logic is particularly well-suited for processes with nonlinear and complex dynamics and can be easily integrated into existing traditional control architectures [5, 6, 7, 8, 9]. A Fuzzy logic-based control system can adapt to variations in arc current and voltage values, and in a nonlinear system, it allows for optimal regulation of electrode movement to maintain arc length within acceptable limits [10,11]. By adjusting the arc length using Fuzzy logic, electrode breakage can be minimized, electrode consumption reduced, and the intensity of the steelmaking process increased, leading to improved product yield.

Results. Based on the above analysis, it is necessary to develop a control system within the fuzzy logic framework that can account for even the smallest variations in electric arc parameters. The functional sequence of managing electrode movement and maintaining arc length within optimal limits using Fuzzy logic in an (EAF) is presented in figure 1.

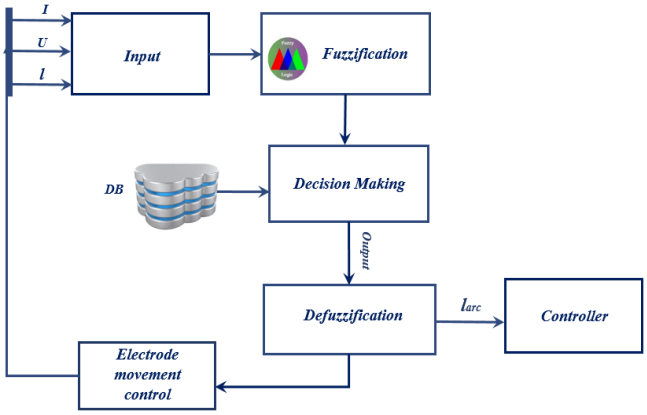

Figure 1. Sequence diagram of regulating electrode movement based on Fuzzy logic to maintain optimal arc length.

As shown in figure 1, the development of a Fuzzy control system for regulating electrode movement in the EAF-30 involves the following stages: initially, the input parameters must be transformed into Fuzzy linguistic sets through a fuzzification process. For this purpose, Fuzzy logic membership functions were developed for the variations in arc current, arc voltage, and arc length.

At the beginning of the primary charge melting process in the EAF, the minimum arc current value starts at 17 kA. Therefore, the lowest acceptable current value was set at 17 kA. The variations in arc voltage were expressed in percentages, and corresponding Fuzzy linguistic variables were defined and subsequently fuzzified.

Note: If the arc current, voltage, and arc length fall within a specific interval, the following fuzzy linguistic terms are used in accordance with the values of Fuzzy variables:

For arc current:

15–19 kA → Very Low → (VL)

17–27 kA → Close to Normal → (CN)

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I > 37 kA → Out of Range → (OR)

Table 1

Critical values affecting arc current and voltage

Cate-gory	Interval (kA)	Desc-ription	I_{max} (kA)	Category	Interval (%)	Desc-ription	U_{max} (V)
ThL	[15; 17; 20]	Very low	17	Boun	[-6; -4]	Very low	375
L	[21; 23; 25]	Low	23	Min	[-4; -2,5]	Low	384
M	[26; 27; 29]	Medium	27	Med	[-2,5; -1,5; 2,5]	Medium	390
H	[30; 33; 35]	High	33	Max	[2,5; 4; 6]	High	416
ThH	[36; 37; 38]	Very High	37	FM	[6; 8]	Very High	425

For arc voltage:

360–380 V → Very Low → (VL)

384–395 V → Close to Normal → (CN)

U > 425 V → Out of Range → (OR)

In the Fuzzy logic-based control system, during the fuzzification stage, arc current and voltage are considered highly variable parameters in the EAF process. The differences in these quantitative parameters are described using membership functions. Given that the variation patterns of input parameters are uncertain and exhibit a naturally exponential character, the use of Gaussian membership functions is considered highly effective for modeling such physical processes. Therefore, Gaussian membership functions were selected to represent arc current and voltage in this Fuzzy logic control framework. These functions are defined according to the following equation (1) within the Fuzzy logic methodology.

$$\mu_{\tilde{A}}(x) = \begin{cases} e^{-\left(\frac{x-x_0}{2\sigma}\right)^2}, & if\ x \in (x_0 - 6\sigma, (x_0 + 6\sigma) \\ 1, & if \quad x = x_0 \end{cases} \quad (1)$$

Using equation (1), Gaussian membership functions were constructed for all the critical arc current values specified in table 1. These functions were visualized using different colors corresponding to their respective influence levels (figure 2).

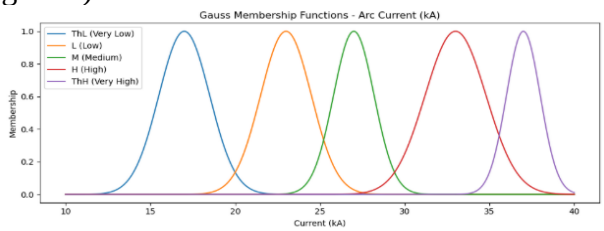

Figure 2. Fuzzy Gaussian membership functions for arc current influencing the electric steelmaking process.

To ensure universality in managing the steelmaking process in EAFs of various capacities, the critical values of arc voltage were expressed in percentage terms. Accordingly, appropriate membership functions were developed based on these values (see table 1 and figure 3).

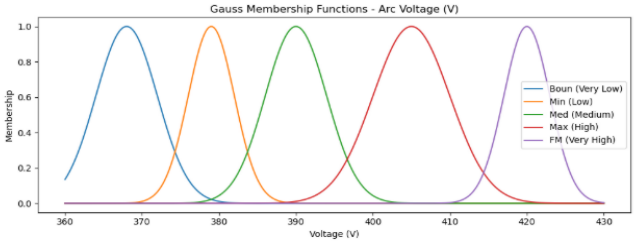

Figure 3. Fuzzy Gaussian membership functions for arc voltage influencing the electric steelmaking process.

After the fuzzification stage, the decision-making mechanism is activated. To determine the resulting output, it combines fuzzy membership functions derived from the knowledge base. As illustrated in figures 2 and 3, the Gaussian membership functions corresponding to arc current and voltage values are merged. In the Fuzzy decision-making mechanism, the Mamdani fuzzy system operates according to its own algorithmic rules, using if–then logic, which reflects the reasoning of an expert familiar with the steelmaking process.

Discussion. In the Mamdani system, the output values are obtained through the centroid defuzzification method. Based on the resulting Fuzzy membership degrees, the system defines optimal arc length boundaries appropriate for the complex nature of the steelmaking process. Following the development of Fuzzy linguistic variables for arc current and voltage, further research was conducted to determine the critical boundary values for arc length, presented in table 2.

Using the Mamdani algorithm, the system is able to automatically determine how many centimeters and in which direction the electrodes should move, based on variations in arc current and voltage. In figure 4, the arc length boundaries derived from the values in table 2—depending on critical arc current and voltage—are shown as a pulse-type membership function graph generated using the Mamdani system.

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Table 2

Critical values for arc length variation levels

Category	Interval (sm)	Description	Arc length critical value l_{max}, (sm)
ThLarc	[2; 5]	Very short (needs to be increased)	5
Larc	[6; 10]	Slightly short (still needs increase)	10
Marc	[12; 24]	Normal length	24
Harc	[26; 35]	Extended length	35
ThHarc	[$l \in [36 < l]$]	Very long (needs to be reduced)	45

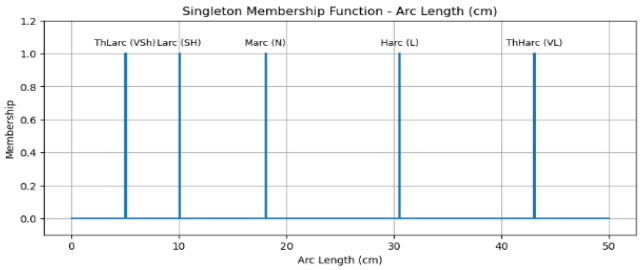

Figure 4. Pulse-type membership function for arc length based on the Fuzzy decision-making mechanism.

According to the data illustrated in figure 4:

When arc length is small, i.e., 2 cm ≤ l < 7 cm, and especially l < 5 cm, the term "Very Short" (VS) is applied, and a signal is sent to rapidly raise the electrodes.

When arc length is in the medium or normal range, i.e., 12 cm ≤ l < 24 cm, the system uses the term "Close" (C) and sends a signal to maintain electrode position within this range.

When the arc length exceeds l > 45 cm, the term "Out of Range" (OR) is used, and a signal is sent to rapidly lower the electrodes.

In this case, the electrodes continue to move downward until the arc length returns to the normal range, at which point a new signal slows down electrode movement to maintain stability. In this Fuzzy control system based on artificial intelligence, the optimal range for managing arc length—from the moment the solid charge begins to melt until the liquid metal state is reached—was found to be approximately 17–20 minutes. Once the primary metal in the furnace bath has reached the liquid state, the electrodes remain immersed, and the melting process proceeds smoothly.

Conclusion. The study confirms the effectiveness of applying Fuzzy logic for controlling the complex and nonlinear technological process of electric arc steelmaking. By analyzing the behavior of key parameters such as arc current, voltage, and arc length within a EAF-30, it was demonstrated that traditional control systems face significant limitations in maintaining stable operation during rapid fluctuations—often resulting in electrode damage and process inefficiencies. To address these challenges, a Fuzzy logic-based control approach was developed using Gaussian membership functions and the Mamdani inference model. This control system accurately responds to variations in arc current and voltage by adjusting electrode movement to maintain the arc length within defined optimal boundaries. The research established critical threshold values for each parameter, and a comprehensive rule base was formulated to guide the decision-making mechanism of the Fuzzy system. Simulation results showed that, within the first 17–20 minutes of the melting process—where electric arc conditions are most dynamic—electrode movement can be efficiently managed to reduce energy consumption and electrode wear. Furthermore, the integration of Fuzzy logic enables adaptive, real-time control, making it a practical and intelligent solution for enhancing the stability, productivity, and energy efficiency of the steelmaking process. The proposed Fuzzy control strategy not only optimizes electrode regulation but also contributes to the digital transformation of metallurgical operations, offering a scalable model for implementation in electric arc furnaces of varying capacities.

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